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Conceptual Design of a Dragonfly-Inspired Nano-Air Vehicle

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1 Introduction

The flight of insects such as butterflies and dragonflies continues to mystify designers with regard to the manner in which they accomplish steady as well as maneuvering flights at low Reynolds numbers. Observations of the supermaneuverable dragonfly "Odonata Anisoptera" (fig. 1 [1]) suggest that the clue to fly lies in their flapping wings. Reviews of the kinematics and the associated flow physics can be found in [2-8]. To understand the flight mechanics, researchers have experimented with live-dragonflies in wind tunnels, deployed flow-visualization techniques, carried out force measurements as well as studied using CFD tools. It has been reported that the peak lift could be as high as 6 times its weight. Based on these studies, successful efforts have been made to mimic the kinematics of insect flight to provide all the degrees of freedom. Extensive research in this area has led to successful development of flapping wing MAVs and Ornithopters. In such machines, the kinematics of the flapping motion is required to generate lift as well as thrust required for flying. Consequently, the energy required for generating both the flapping motion as well as for thrust is demanded from the powerplant, which leads to limited endurance. However, if the two forces could be de-coupled by (a) generating lift Consequently, the energy required for generating both the flapping motion as well as for thrust is demanded from the powerplant, which leads to limited endurance. However, if the two forces could be

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de-coupled by (a) generating lift by fixed wings mimicking the physics of lift generation (rather than mimicking the kinematics) (b) use power-plant only for thrust generation purposes (c) conventional control surfaces for pitch, roll and yaw-control, an efficient biomimic of the dragonfly could be achieved, leading to fixed wing aircraft of Nano-Size (termed Nano-Air-Vehicle) with long endurance.

Visual observations of flight of the dragonfly suggest that during their steady and level flight, while the fore-wings have a small amplitude 'twitch', the rear wings are stationary. It may therefore be theorized that the twitching motion results in the formation of the "Starting Vortex" which leaves the front wing and passes over the rear wing. The rear-wing alligns itself such that the vortex transits over its upper surface, which causes a lift force. As soon as the vortex leaves the rear-wing, the front wings twitch again, to create a new starting vortex and the phenomena repeats, which can lead to quasi-steady lift. If the dynamics of the two events are properly synchronized, generation of quasi-steady lift seems possible. From this perspective, the fore-wing can, in principle be regarded as a vortex-generator and the rear wing as a lifting surface which produces high values of vortex-induced mean lift. However, to qualify as a wing to be used in an aircraft, the configuration must generate sufficient value of the Lift-to-Drag ratio.

Fig. 1 Photographs of a Dragonfly [1]

The simplest vortex generator and a lifting surface that one can think of are a circular cylinder and a flat plate, as shown in fig. 2, where (x/R) and (z/R) are geometrical parameters, as shown.

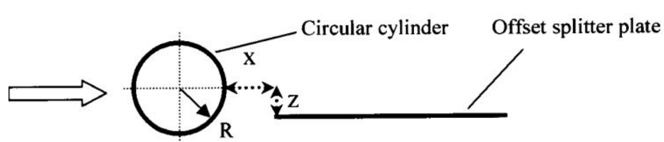


Fig. 2 Vortex-Generator and Lifting-Surface [10]

In the literature, the pioneering concept of interfering the base flow of a circular cylinder by a plate (splitter-plate) was reported [11] wherein a symmetric splitter with appropriate geometric dimensions was found to modify / control / suppress the vortex shedding from a circular cylinder by stabilizing the hydrodynamic instability associated with the natural vortex shedding phenomena at low Reynolds numbers. The splitter-plate, along with suppression of vortex shedding, resulted in a symmetric and steady flow pattern accompanied by increased base pressure and consequent drag reduction. Subsequently, enormous variants of the splitter plate, such as upstream splitter plate, flexible, semi-flexible, short, long, porous plate, rigid corrugated plate, etc, have been studied. In bulk of these studies, focus is on drag reduction / control / suppression of vortex shedding or Vortex Indued Vibration (VIV). In the present context, the concept is to generate steady lift using an offset splitter-plate (fig. 2 [11]), an aspect that has attracted only little or no attention in the literature. Computational results using OPENFOAM have been reported [11] for one of the configurations at Re = 7500 (mid-range for Dragonflies). In the steady-state condition (fig. 3), a pair of attached twin-eddies (Anticlockwise vortex A1 and Clockwise vortex (C1) at the rear of the cylinder and a trapped Clockwise vortex (C2) over the lifting surface occur, with suppression of vortex shedding.

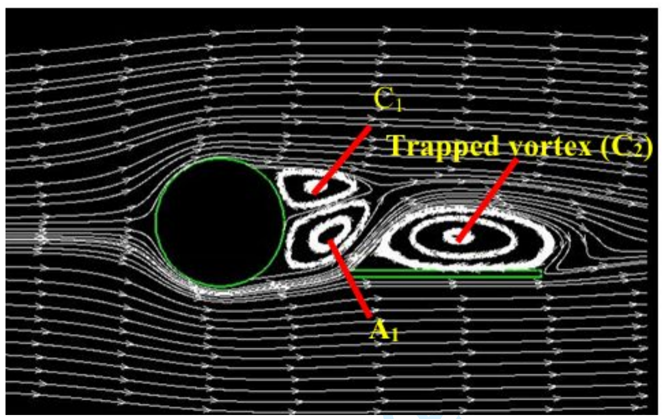


Fig. 3 Computed steady-state streamlines [11]

The simulations indicate that the air-flow in the lower region in-between the cylinder and the leading edge of the lifting surface, splits into two components, one which travels over the lifting surface over the trapped vortex C2) and the other which turns upstream towards the cylinder as the anticlockwise vortex A1. The flow over the cylinder on the upper side separates and forms a clockwise vortex C1. A1 and C1 pair together, thereby forming a twin-eddy like structure, with a singular point occurring above the trapped vortex C2. The vortex C2 reattaches the flow near the trailing edge, in a sense satisfying the Kutta condition at the trailing edge. After the initial transients, vortex shedding behind the configuration stops. The corresponding steady-state pressure contours (Fig. 4) clearly indicate the following: (i) Occurrence of stagnation point at the front of the cylinder (ii) suction around the top and bottom of the cylinder (iii) Occurrence of low pressure over the upper side within the trapped vortex of the lifting surface (iv) occurrence of a stagnation point around the leading edge of the lifting surface (v) occurrence of increased pressures on the lower side of the lifting surface. As a consequence of (ii) to (iv), the configuration is expected to generate a steady lift force. Fig. 5 shows the computed Cl, Cd and (Cl/Cd). It may be noted that after the initial transients, the configuration achieved (Cl/Cd) ~ 3.0 which is inadequate, but demonstrates that the configuration is capable of generating lift. The use of trapped vortices for separation control has been well studied and reported [12-16], but not satisfactorily demonstrated through experiments. Of particular attention is the work reported [13-14] which claims the extraordinary lift performance of a glider which trapped a vortex on the upper side to achieve high lift at low-speeds. However, there have been practically no experimental evidences.

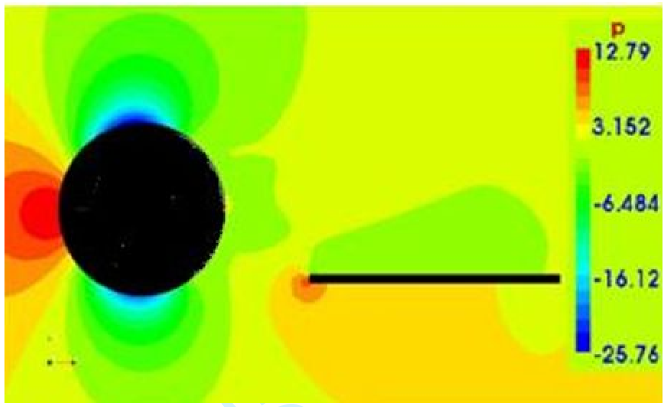


Fig. 4 Computed steady-state presssure contours [11]

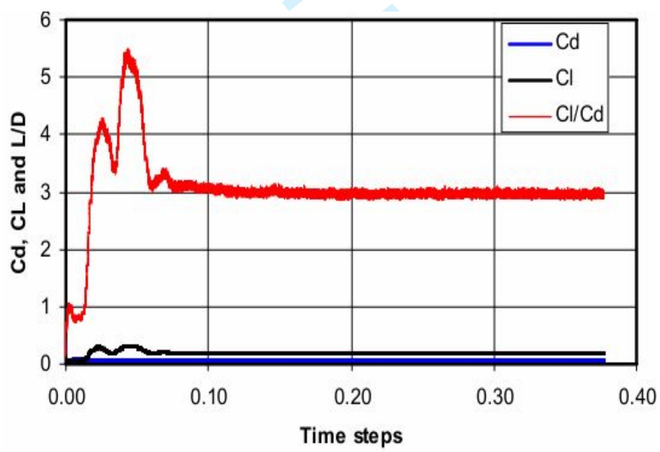


Fig. 5 Computed Cl, Cd and (Cl/Cd) [11]

Optimization studies to maximize the lift to drag ratio, involving geometries of the vortex generator, the lifting surface, (x/R), (z/R), angle of attack (angle between the chord of the vortex generator and the freestream) in the range of Re of dragonflies has revealed a configuration which provides (L/D) ~14 in the steady-state at Re = 15000 (fig. 6, 7). The corresponding streamline patterns clearly show significantly enhanced region of the trapped vortex over the lifting surface (fig. 8). Details of these studies are reported in [11, 17]. These observations clearly indicate the occurrence of a bound vortex and stagnation point close to the trailing edge, consistent with the well known Kutta-condition required to be satisfied for lift generation. Interestingly, a study reported based on tests on a tethered live dragonfly in a wind tunnel [2] has detected the occurrence of a bound vortex on the fore-wings of a dragonfly (fig. 9). Thus, the present computational results agree with the occurrence of a bound vortex. However. the present computational results indicate the occurrence of bound vortex on the rear-wing, whereas experimental observations indicate the bound vortex on the fore-wing [8] of a dragonfly. However, the experiments are based on a flapping live-dragonfly whereas the computations are on fixed wings. Thus, it can be said that the present configuration mimics the physics of flight of the dragonfly, rather than the kinematics.

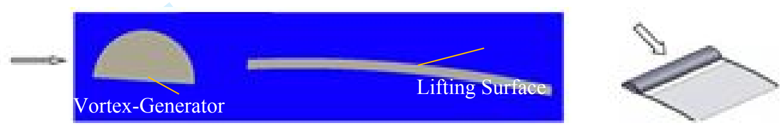


Fig. 6 Geometry of the optimized profile geometry

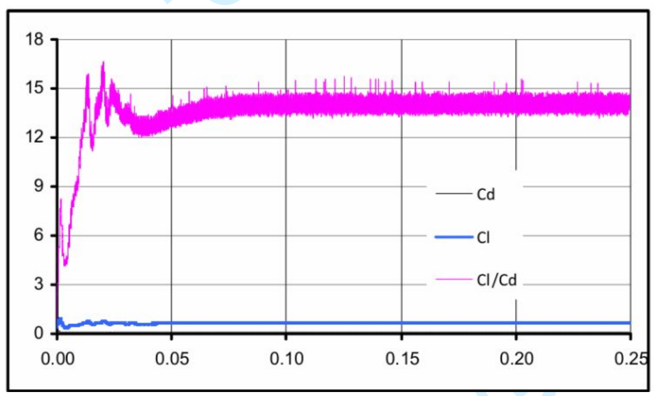


Fig. 7 Cl, Cd and (Cl/Cd) at Re = 15000 [11, 17]

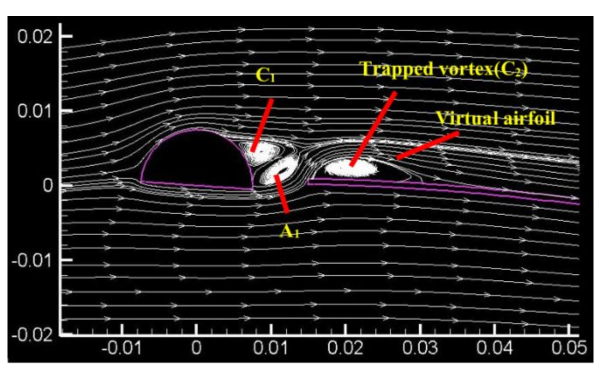


Fig. 8 Extended trapped vortex over the lifting surface [11, 17]

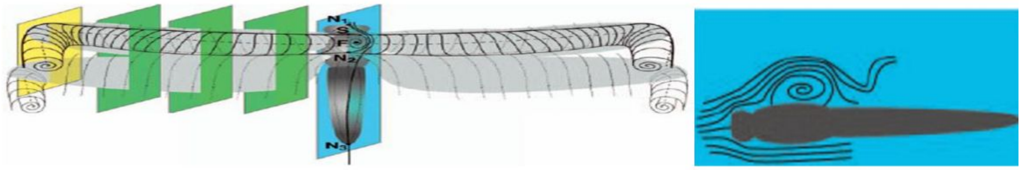
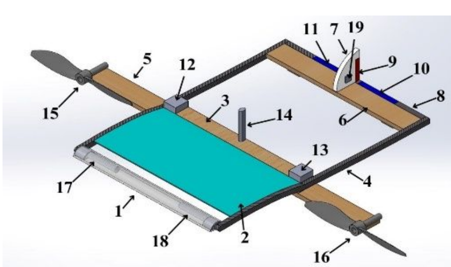


Fig. 9 Bound-vortex over the fore-wings of a dragonfly [7]

One of the important limitations of flapping wing MAVs is that bulk of the available power is utized in the kinematics of the flapping motion, leaving rather little power for cruising. This sets up limitations on the endurance of flight of flapping wing MAVs. In contrast, the present methodology mimics the physics of flapping, but with fixed wings and thus contributes to enhanced endurance.

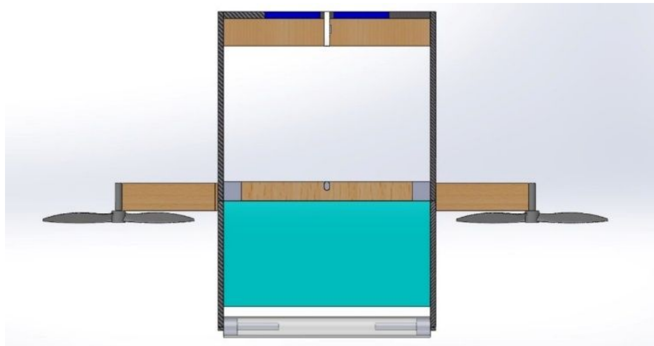
2 Design of Nano-Air-Vehicle (NAV)

Even though the referred studies [11, 17] provide the framework for design of a wing that mimics the steady flight of a dragonfly, the wing alone itself cannot fly: it needs a powerplant to provide the thrust force, stabilizers and control surfaces to perform a flight. This aspect is reported in the present work. Figure 10 [18] shows a typical conceptual view of the NAV, designed to be flown using conventional Remote-Controls used on Aeromodels. The forebody (Item 1) is the vortex-generator (semi-circular cylinder with chord at a small angle of incidence to the freestram) mounted upstream of the lifting surface (Item 2, thin surface shaped like a circular arc. Item 3 is the mid-rib which holds 1 and 2 on the airframe (Item 4, tail boom). Item 5 is a rib which supports two powerplants (Items 15 and 16) powered by batteries (Items 17 and 18) located within the vortex generator (Item 1). Items 7 and 8 are the vertical and horizontal stabilizers located near the end of the tail-boom (Item 4). The elevators and rudder are marked as items 8, 11 and 9. 10 and 11 can be operated together as elevators or differentially as elevons. Roll and yaw controls can also be exercised by differential speed controls of powerplants 15 and 16 using speed controllers 12 and 13. Item 14 is the antenna for communication with Remote Controls.

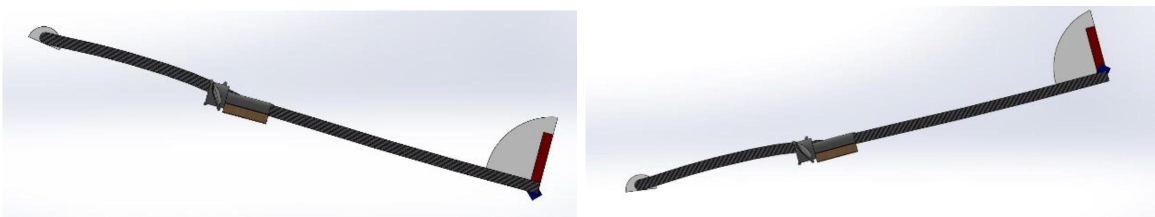


No	Description	No	Description
1	Forebody	9	Rudder
2	Lifting Surface	10	Elevon 1
3	Mid-Rib	11	Elevon 2
4	Airframe	12	Speed Controller 1
5	Powerplant Rib	13	Speed Controller 2
6	Boom	14	Receiving Antenna
7	Vertical Stabilizer	15	Powerplant 1
8	Horizon. Stabilizer	16	Powerplant 2

(a) Overall design with control surfaces



(b) Locations of Rudder and Elevon Servos



(c) Ascent and Descent modes

Fig. 10 Conceptual design of NAV [18]

2.1 Construction and Proof tests

The vortex generator and the lifting surface were 3-D printed using PLA plastic and assembled on the tail boom. Balsa wood strips were used to reinforce side-frame. All-up weight of the model was less than 18g. The overall dimesions were 11 cm in length and 8 cm in width. Demonstration of flyability is the first and foremost priority in the development of any new concept. Since the flight velocities of dragonflies are quite low (typically 2-3 m/s), obtaining the aerodynamic parameters on the NAV configuration is a challenge. Further, design value of the static margin is also a challenge since the aerodynamic center of the NAV featuring separated flow with a trapped vortex, needs to be experimentally determined. Hence, these aspects need fine-tuning through test flights. Hence, tests were carried out in constrained condition through bench-tests and in ground tests. For bench tests, a hand-held frame, hinged near the tail-plane such that the wing can rotate about the hinge-line due to the lift force was developed. A domestic air-cooler, which produces a typical wind velocity of 2-3 m/s (corresponding to Reynolds number of about 15000 based on wing chord) was used. Figures 10 and 11 show typical snapshots of the wing when it is not facing the wind (fig. 10) and when it is introduced into the wind stream (fig. 11). Video-recordings of the experiments can be found in Ref. [19].

(a) Model not exposed to wind

(b) Model exposed to wind

Fig. 11 Screenshots showing the lifting capability of NAV in front of an air-cooler

Field-tests were carried out by restraining the horizontal tail plane with a string, held in hand and allowing the wing to deflect while riding a scooter at low-speeds. Video-recordings are available [19]. Typical snapshots are presented in in fig. 12.

(a) Model at small incidence

(b) Model at moderate incidence

Fig. 12 Demonstration of lifting capability in field-test

Conclusions and Recommendations for Further Work

The present results show that mimicking the physics rather than the kinematics is the key to build nature-inspired fixed-wing nano-air vehicles, which could be as efficient as dragonflies. While the dragonfly achieves steady flight due to a trapped vortex above the rear-wing, the NAV achieves the same result by trapping a vortex over the rear-lifting surface. Since the lift generated on the NAV is largely due to the trapped vortex and separated flow over the upper surface, reliable determination of the location of aerodynamic center is best done by experiments. However, being a low-speed machine, carrying out wind tunnel tests to accurately determine the aerodynamic coefficients, determine the aerodyanic center and design the stabilizers and control surfaces for the required static margin is extremely complex. On the other hand, flight-tests on prototypes is a more practical solution. Hence, prototypes are currently being designed.

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